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Arthur St. Clair Wright

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THESIS

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A Model Sonar Technique for Shallow Water

by

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Submitted in partial fulfillment of the
requirements for the degree of

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ABSTRACT

An experiment was performed in a small laboratory tank to study the feasibility of modeling an active sonar in a shallow water environment. The modeling frequency of 1000 kHz in a two meter tank indicated fair compatibility with theory for the short scaled ranges studied. An initial spherical spreading loss followed by a cylindrical spreading loss, bottom loss effects, and Lloyd mirror interference were observed. The methods were suitable for future modeling experiments.

REY, CALIF. 939

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ACKNOWLEDGEMENT

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I. INTRODUCTION

The growing complexity and magnitude of underwater acoustic systems and the high cost of full scale field work dictate that a technique in which a sonar system could be scaled down or "modeled" prior to field studies would be most useful. In addition model techniques could be used to isolate and study the various parameters affecting the transmission of sound through shallow water.

The basic idea of scaling is to assume that range is proportional to wave length, or that a higher frequency and shorter range can be compared to a lower frequency and longer range. Then if workable techniques could be developed, studies in small laboratory tanks would provide much valuable information.

There are two general theories dealing with the propagation of sound in shallow water: Ray theory and Normal Mode theory. Ray theory represents the sound field as a sum of ray contributions for the source and its images in the surface and bottom. Normal Mode theory represents the sound field in terms of a summation of normal modes which are complex functions, each representing a wave traveling outward from the source with an amplitude that is a function of source, receiver, and water depths. In general, Ray theory is more convenient to use at short ranges, where there are fewer rays to handle. Normal Mode theory is more appropriate at long ranges because of the greater attenuation with distance of the higher order modes. A crossover range between the regions of convenient usefulness of the two theories is given by Urick [1]:

$$r = H^2/\lambda$$

where r = crossover range

H = water depth

λ = wavelength

Many factors affect the propagation of sound. A few are spreading, temperature, temperature gradients, salinity, sea state, bottom composition, bottom contour, presence of suspended matter in the water, and interference effects of surface and bottom reflected rays. Obviously any model technique would like to study these parameters individually. If environmental field and laboratory data were found to be compatible with theory then the characteristics of a model sonar could also be studied in the laboratory tank.

Most present day acoustic ranging systems employ an outgoing directed beam formed by an array of many transmitting transducers. This beam can be referred to in terms of acoustic energy, power or intensity levels, beam width, directivity, and side lobes. The energy from this beam strikes a target and is reflected to the receiving transducers which may or may not be the same as the transmitting transducers. If the transducers are reciprocal the system will convert electrical energy into acoustic energy with a certain efficiency factor and receive any returned acoustic energy reflected by a possible target as electrical energy reflected by a possible target as electrical energy reduced by the same efficiency factor. In the laboratory a single piston transducer can transmit and receive beams that have the same characteristics as the beam of an array.

The experiment described herein is concerned with a sonar that utilizes a wavelength two or three orders of magnitude less than that occurring in an ocean environment. There were three objectives. First, to construct a sonar for use in a scale model situation; second, to determine a standard set of equations compatible with model studies; and third to compare the measured results with available theory.

II. THEORY

A. MODELING CONSIDERATIONS

The scaling mentioned in the introduction can be applied to a shallow water environment for both depth and range. In this paper 1000 kHz was chosen as the laboratory frequency because it was felt that the corresponding wavelength in water, 0.15 centimeters was the smallest that could be conveniently studied in a model. The greatest interest in active sonar systems today covers the range from one to ten kilohertz. This results in scale factors of 1000 and 100 respectively. The following table gives equivalent ranges and depths for the above frequencies given a tank length of two meters and depths of five and twenty centimeters.

Equivalence Table

Environment	Frequency	Range	Depth	
Laboratory	1000 kHz	2 meters	5 centimeters	20 centimeters
Ocean	10 kHz	200 meters	5 meters	20 meters
Ocean	1 kHz	2000 meters	50 meters	200 meters

A. B. Wood did extensive studies of propagation losses in model tanks for various parameter changes in 1958 [2]. His work has been used as a general guide throughout.

B. PISTON TRANSDUCER THEORY

A voltage applied to either side of a thin circular piezoelectric disc causes vibrations at the surfaces of the disc at a frequency

$$f = \frac{k}{t}$$

where t = thickness

k = constant for a particular material

When one of these small discs is mounted in a suitable holder and immersed in water to provide loading, an axial acoustic beam pattern is formed consisting of a major lobe and several side lobes. If the mounting pressures are symmetric, this pattern will also be radially symmetric with respect to the axis. The width of the major lobe is given by Kinsler [3] as

$$\theta = 2 \sin^{-1} .61 \frac{\lambda}{a}$$

where θ = beam width in degrees

a = piston radius

λ = wave length

A system with such a beam is said to have a directivity index:

$$DI = 10 \log \frac{I_o}{I_{ref}}$$

where I_o = axial acoustic intensity at some distance, r.

I_{ref} = intensity at the same distance of an omni-directional transmitter radiated at the same power.

Finally, a piston transducer has a near field effect that causes a series of intensity maximums and minimums but after a certain range is attained, called the far field, the intensity decreases according to a particular spreading law.

C. PROPAGATION THEORY

When one considers underwater acoustic systems the standard equation is the Sonar Equation. This is set forth in various forms for the maximum range attainable for the noise limited, the reverberation limited, and the passive listening case. The many authors use a wide variety of symbols but for this paper only one form shall be considered.

$$SL + T = 2H + E$$

where SL = Source level — dB re one inch

T = Target strength — dB

H = One way transmission loss — dB

E = Target echo level at the receiver — dB

Source level, SL, is normally considered to be the intensity of sound emitted by the transducer at a reference distance of one yard from the effective acoustic center expressed as a spectrum level in decibels relative to microbar in a 1 cps band. However since this paper deals with scaling, the reference distance of one yard is unrealistic and the source level reference distance will be one inch. Intensity is given by:

$$I = \frac{p^2}{\rho c}$$

where p = effective acoustic pressure — dyne/cm^2 = microbar

ρ = density of medium — gm/cm^2

c = velocity of sound in the medium — cm/sec

The effective acoustic pressure and the intensity can be found by means of a reciprocity calibration using a reference distance of one inch [1,3]. Since we are concerned with a directed system the reciprocity calibration and the source level are "on axis" computations.

Target strength, T, is similar to source level and is defined as the ratio of echo intensity at one inch to incident intensity at the target expressed in decibels. For a rigid spherical target where the wave length of the incident wave is much less than the sphere diameter [1]:

$$T = 20 \log \frac{a}{2}$$

where a = radius — inches

Transmission loss, H, has been the subject of much discussion and there are many models based on theory and empirical derivation. All authors agree that there is a spreading loss term to account for geometric spreading and subsequent loss of power, and an absorption term to account for energy removed from the beam as a function of frequency and range (R). In general, in deep water spreading is considered to be spherical (20 log R), and in shallow water spreading is considered to approach a cylindrical loss (10 log R) after an initial period of spherical spreading. Mathematical models for absorption vary widely at low frequencies, but at the high frequencies used in modeling, most authors agree that decibel loss is a linear function of range. Urick states the loss at 1000 kHz is 150 decibels per kiloyard or 0.3 decibels at two yards [1]. If a laboratory tank were two yards long this absorption loss would be negligible.

Other significant parameters that affect propagation are bottom and surface reflection losses, temperature gradients, and suspended solids and gases. Each time a ray is reflected from the bottom some energy is lost due to partial transmission into the bottom according to Snell's Law. If the bottom acoustic velocity and density are known the decibel loss per reflection can be calculated. The air-water interface is a pressure release surface and all energy is returned into the water with a 180 degree phase change. If the surface is perfectly flat all the acoustic energy goes in the specular direction but as the surface becomes rougher, more energy is reflected off in other directions. Under high sea-state and long range conditions no surface reflections augment an active sonar system. Under laboratory conditions as long as the bottom characteristics are known, their theoretical effects on sound propagation can be predicted.

Temperature gradients affect the propagation of sound by causing the sound velocity to change with depth resulting in a bending of the "rays". In a laboratory with constant temperature no gradients are assumed to exist and all rays are considered straight.

Suspended solids and gases act as sound scatterers and if concentrated enough can constitute a false target. If there is a high density of such scatterers a system would be reverberation limited and its maximum range would be less than the noise limited case. In the ocean, these scatterers can be air bubbles, solid particles, and biological forms. In the laboratory they are air bubbles, dust, and various micro-organisms inherited from the air. Ideally, a laboratory tank should be in a sterile atmosphere and covered when not in use. The water in the tank should also be boiled prior to use to ensure a paucity of entrapped gasses. However for a first effort the effects of scatterers could be discounted with negligible effect on gross characteristics.

D. LLOYD MIRROR EFFECTS

The bottom reflected and the surface reflected rays interfere with the direct rays in either a constructive or destructive manner depending upon the phase differences due to varying path lengths. This effect is called Lloyd mirror or image interference. For the surface image interference only, Urick [1] gives the following for intensity at a point after one reflection:

$$I = I_0 (1 + \mu^2 - 2\mu \cos \omega\tau)$$

where I = Intensity

I_o = Intensity of direct ray alone

μ = Amplitude reflection coefficient of surface

ω = Frequency in radians per second

τ = Time delay caused by the longer path of the surface reflection

By reworking Urick's equation for both surface and bottom image effects the following is obtained:

$$I = I_o [1 + \mu_1^2 + \mu_2^2 + 2\mu_1 \cos \omega\tau_1 + \mu_2 \cos \omega\tau_2$$

$$+ 2 \mu_1\mu_2 \cos \omega(\tau_1 - \tau_2)]$$

Where μ_1 and τ_1 relate to the surface reflection coefficient and the surface reflection delay and μ_2 and τ_2 relate to the bottom. In this equation the proper sign must be put in for the reflection coefficient whereas in Urick's equation the proper sign has been inserted. As sea-state increases the magnitude of μ_1 decreases and in general for a sand bottom μ_2 is about 0.4. In a natural environment therefore, Lloyd mirror effects can be expected to decrease as range, and the number of surface and bottom reflections, increase.

III. EQUIPMENT

A. GENERAL

Equipment used in this experiment fell under one major category: that which was readily available and compatible with space limitations. The tank, electronic equipment, and peripheral mountings were procured or manufactured locally. The transducer elements were furnished by Gulton Industries [4] and the transducers were assembled by the author. It was assumed that a matched pair of discs would yield a matched pair of transducers — one for the transmitter and one for the receiver.

B. TANK

A wooden tank with inside dimensions of 75" x 72" x 15" was available and therefore appropriated. The inside of the tank was coated with neoprene over pressure release plastic foam. There were small rills approximately one millimeter deep that would be expected to interfere with sound transmission in the "down-range" direction. The use of pulse techniques precluded any standing waves. A previous leak had resulted in a fiber glass patch on one side of the tank, but this did not interfere with measurements along the down-range side.

A set of portable stainless steel tracks with lucite runners was constructed. The runners were inletted in the center to allow for vertical motion of the transducer stems. A screw mounted face plate provided sufficient tension to hold the transducers at the desired depth. The portable feature of the track allowed it either to be aligned longitudinally down-range for transmitter to receiver propagation loss measurements or aligned cross-wise for side by side operation of the transmitter and receiver as a sonar in the down-range direction.

C. TRANSDUCER CONSTRUCTION

Barium titanate crystals 1/8" thick and 1/2" in diameter were used as transducer elements. The transducer body was a cylinder of lucite, inletted for the element and drilled and tapped for the stem attachment. The stem is copper tubing 3/8" in diameter and 15" in length. Shielded wire was used for the lead within the stem. The connector at the top was a BNC connector which had been turned down on a lathe to provide a close fit to the inside of the stem. In construction the wire lead was first soldered to a BNC connector, pulled tight and finally attached to the transducer element. In transducer #1 the wire lead was soldered to the inner face and a short 3/4" ground lead was soldered at the outer face and the copper stem. Seating compound was commercial silicone marine sealer. In transducer #2 no soldered connections were used. The wire lead through the lucite body was simply cut off at about 1/2", all strands except one removed, and the remaining single strand was coiled around the inlet for a pressure connection. Silicone marine sealer was applied around the rim of the inlet and the element seated under pressure for twelve hours. Instead of a ground lead, two coats of silver paint were applied in a line from the outer element face, over the lucite body, to the stem. In both cases the completed assemblies were dipped in neoprene. Figure 1 shows the details of a transducer head and figure 2 shows a transducer mounted on the lucite runner.

D. TARGET

Any target could be used in a modeling situation as long as its target strength was known for each aspect angle. The target strengths for various types of submarine hulls have been found empirically both in model studies and in the ocean environment [5]. However the easiest target to use in a

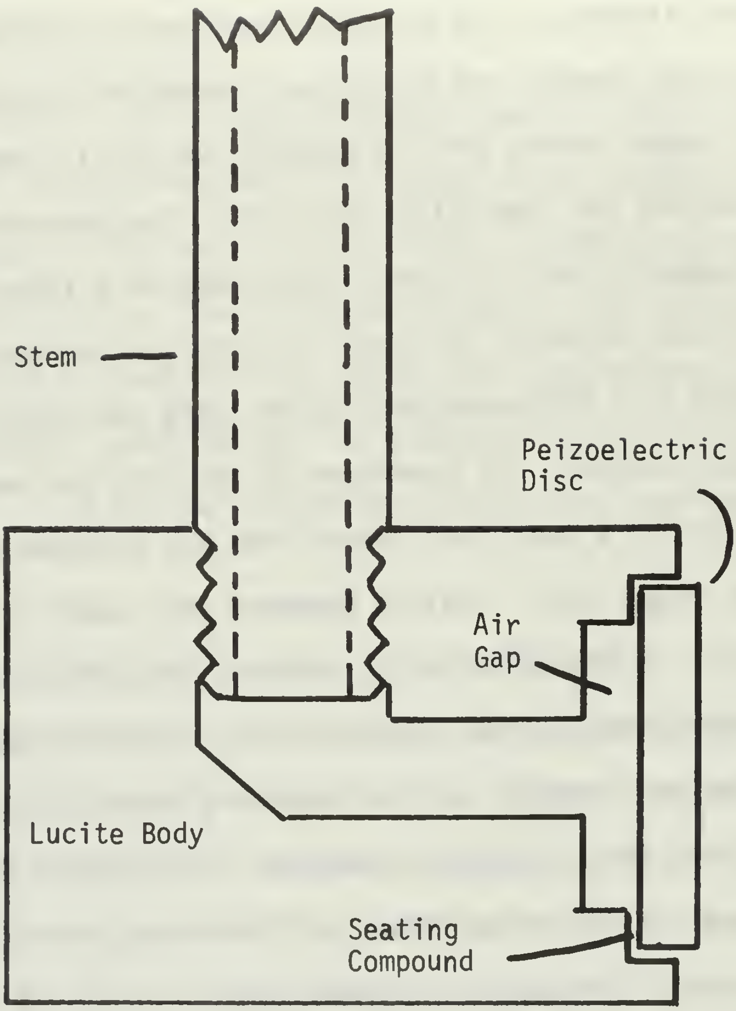

Figure 1 Transducer Head Details (not to scale)

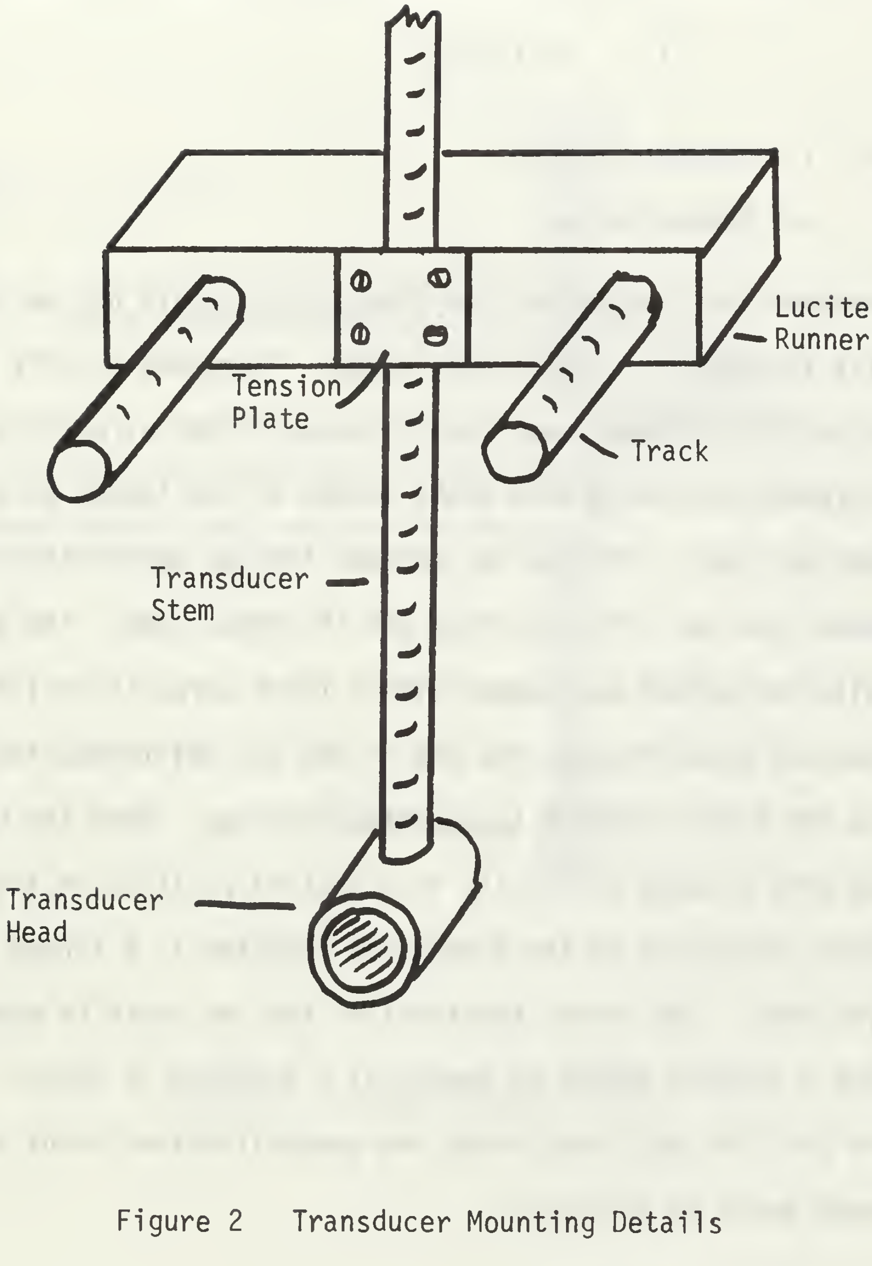

Figure 2 Transducer Mounting Details

model is a sphere which is easy to align and has a constant target strength for all aspects. A 5/8" steel ball bearing was procured and attached to a stiff 18" length of wire. This sphere provided a diameter to wave length ratio of more than ten and a target strength of:

$$T = 20 \log \frac{a}{2}$$

where T = target strength

a = sphere radius

However this target was too flexible and could not be adjusted exactly in depth at a particular range. Therefore a stiff 1/16" diameter brass rod 18" in length was used in place of the wire. This brass rod was threaded for the middle eight inches of its length at a rate of 24 threads per inch. The rod was screwed into an appropriately tapped aluminum flat bar 1/4 inch thick and 15 inches long. The end of the rod opposite the sphere was capped with a thumb screw to facilitate turning. A nylon set screw through the end of the bar maintained tension on the rod as the brass wore due to repeated turnings. When the bar, rod, and sphere were clamped vertically in a desired position in the tank, one complete revolution on the thumbscrew resulted in a target depth change of 1/24 inch. The finite thickness of the rod could be expected to reflect a certain amount of energy as a function of depth. The value of ka for this rod was about three and generalizations about its target strength would be difficult.

E. ELECTRONIC EQUIPMENT

Several items of electronic equipment were used before an acceptable system was achieved. The pulse generator and square wave generator performed satisfactorily throughout the experiment. The first amplifier had

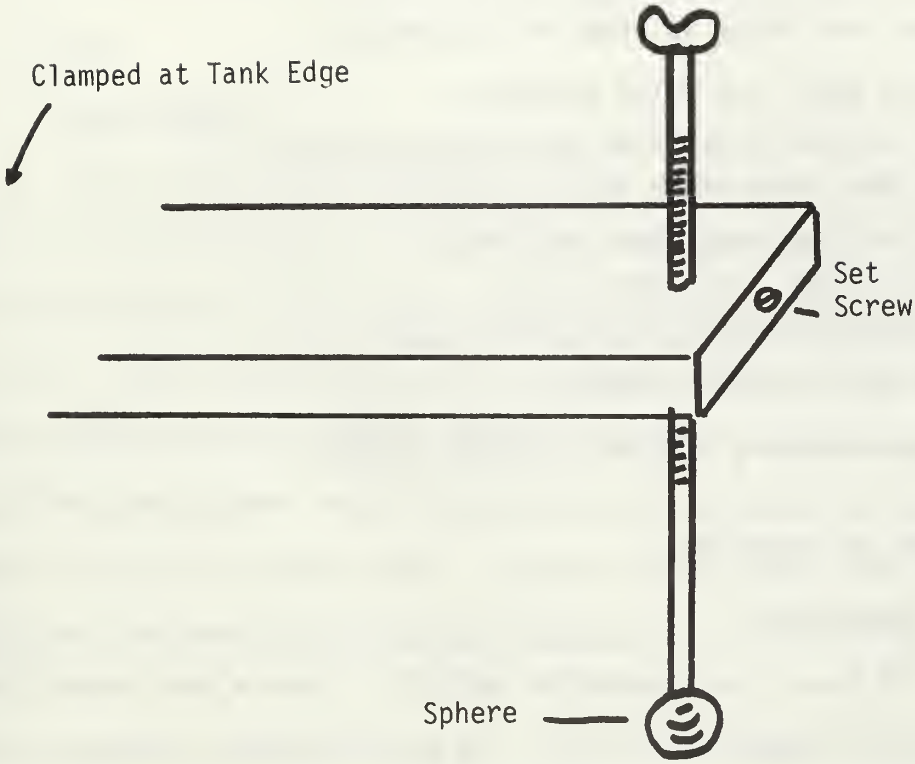

Figure 3 Target Construction

an amplification factor that varied with voltage level. The second amplifier was satisfactory. The first oscilloscope did not have sufficient preamplification for the longer range targets. The second oscilloscope did not have sufficient storage time nor could it be operated in a non-storage mode. The third oscilloscope was satisfactory and also shunted off the higher harmonics of the square wave to ground. The equipments are listed in order of use below:

DATAPULSE MODEL 101 Pulse Generator
HEWLETT-PACKARD MODEL 220A Square Wave Generator
DONNER MODEL 6100 Video Probe Amplifier
HEWLETT-PACKARD MODEL 466A Amplifier
TEKTRONIX MODEL 515 Oscilloscope
HUGHES MEMOSCOPE MODEL 105 Oscilloscope
ANALAB TYPE 1100 Oscilloscope

All connections were made with coaxial cable.

F. THEORY OF OPERATION

1. Transmitter

The square wave generator delivers a square wave proportional in frequency to a negative DC bias. The pulse generator provides this bias by delivering an unsymmetrical square wave that is much lower in frequency than the output of the square wave generator. Thus the on-time of the square wave generator is the pulse length of the output. The high Q of the transducer makes it act like a crystal filter and the first harmonic of the output square wave is picked off. The result is an output sine wave pulse at the thickness resonant frequency, 1055 kHz, of the transducer element. Pulse width and repetition rate are adjusted by varying appropriate controls on the pulse generator.

2. <u>Receiver</u>

The receiver section consists of the receiving transducer, the amplifier and the oscilloscope. The amplifier has either a 20 dB or a 40 dB voltage gain. A transmit-receive switch was not considered necessary because the transmitting and receiving transducers had similar characteristics and their beam patterns overlapped in the far field of the pistons.

3. <u>Measurements</u>

Due to pulse techniques all voltage levels were read from the face of the oscilloscope and converted to intensity decibel levels by hand calculations. Several other signal processing schemes could be devised. Arcuni in [6] shows one such scheme. The nature of the particular experiment and whether intensity, power, or energy were to be the primary measurement would dictate the type of signal processing scheme to be used in future work. However in this case, the "eyeball" method was considered sufficiently accurate.

IV. PRELIMINARY CALCULATIONS

A. RESONANT FREQUENCIES

Resonant frequencies of each transducer were first found separately in the continuous wave mode. Both had a major resonance just over 1000 kHz. This indicated a matched set of transducers at that frequency so then the system resonance was found in the mode in which the sonar set would be used. The maximum receiver output in the pulse mode occurred at 1055 kHz as measured on the oscilloscope face on a reduced time scale. Using the formula:

$$c = f\lambda$$

where c = velocity of sound in water

f = frequency

λ = wavelength

The system wavelength was found to be approximately 0.15 centimeters.

B. SYSTEM RESPONSE LEVEL

In this experiment, system response level is analagous to source level, transmitting directivity index and receiving directivity index used in the Sonar Equations of other authors [1,3,5], because all measurements are taken "on axis". The conversion of volts to microbars at the transmitter and microbars to volts at the receiver is simply a factor which drops out in conversion to decibels. The receiver-amplifier-oscilloscope output was read for all values of returned target echo. Therefore system response level is simply the receiver output at a distance of one inch from the transmitter converted to decibels. For convenience the same transmitter output voltage was used in all cases.

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Then:

$$SRL = 20 \log V_1$$

where V_1 = received signal at 1" on axis

SRL = system response level in Db re one millivolt at one inch.

Average measured value of V_1 was 19200 millivolts using transducer #2 as the transmitter and transducer #1 as the receiver. Therefore:

$$SRL = 20 \log 19200 = 20\ (4.284) = 85.68\ \text{dB}$$

C. DIRECTIVITY

Directivity was measured at a constant range of one meter so that nulls and peaks could be found accurately. Since system response level in this paper includes directivity this transducer parameter is only of interest to show that we do have a narrow beam width as predicted by theory. The receiving transducer for this measurement was a 1/4 inch long cylindrical barium titanate probe that had omnidirectional characteristics in its horizontal plane. Beam patterns obtained form the directivity measurements were almost identical and one is plotted in figure 4. The directivity indexes are graphically computed by averaging the voltage levels over 360°, dividing this result into the peak value on axis, and taking 20 log of the quotient.

Theoretical value of major beam width

$$\theta = 2 \sin^{-1} (.61 \frac{\lambda}{a}) = 16.6°$$

Observed values of major beam widths:

#1: $\theta_1 = 14°$

#2: $\theta_2 = 14°$

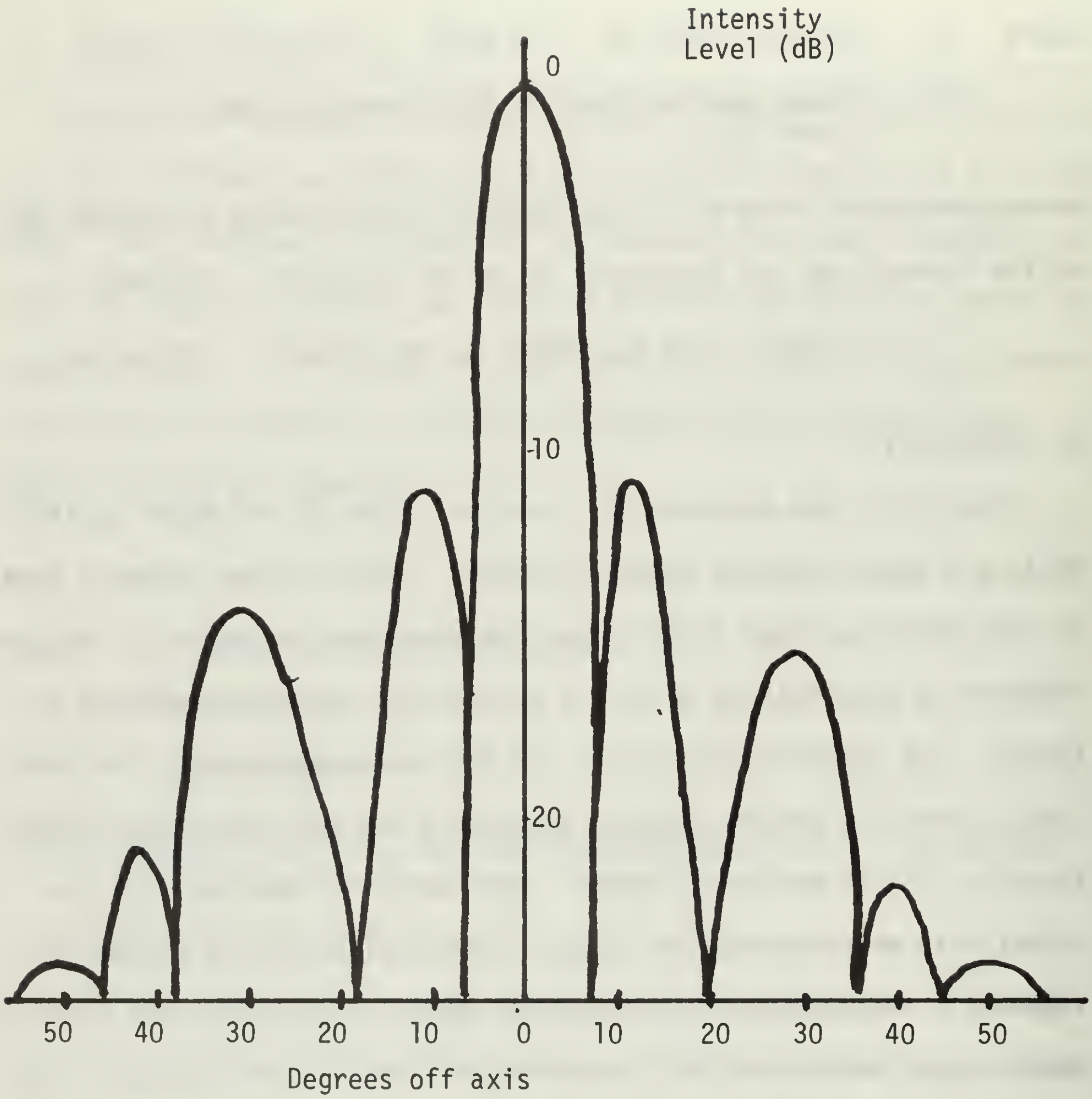


Figure 4 Directivity

Graphically computed values of directivity:

$$DI = 10 \log \frac{I_o}{I_{ref}} = 20 \log \frac{V_o}{V_{ref}}$$

where V_o = axial value of receiver probe voltage

V_{ref} = average value of receiver voltage over 360°

$$DI_1 = 20 \log \frac{95}{4.08} = 27.32 \text{ dB}$$

$$DI_2 = 20 \log \frac{96}{4.05} = 27.52 \text{ dB}$$

D. TRANSMISSION LOSS

The characteristics of the tank theoretically should cause spherical spreading to a certain point and cylindrical spreading thereafter. Using transducer #2 as a transmitter and transducer #2 as a receiver at various ranges the gross loss features of the tank can be found. The relative size of the piston faces compared to wavelength should eliminate minor fluctuations predicted by Normal Mode and Lloyd mirror theory. This was done for three positions each of the transmitter and receiver: surface, mid-depth, and bottom and for several ranges from 10" to 60". When the transmitter and receiver were not vertically positioned together the beam characteristics caused high loss indications at the closer ranges. The receiver voltage levels for the three receiver positions with the transmitter in the middle have been averaged for each range, converted to decibels and normalized to zero dB at one inch in Table I.. The loss data are plotted in figure 5.

TABLE I

TRANSMISSION LOSS CALCULATIONS

TRANSMITTER: MID-DEPTH

RECEIVER: SURFACE, MID-DEPTH

Range	1"	10"	15"	20"	30"	40"	60"
Sum of Receiver Levels: V_R	5760	1300	1120	970	710	610	560
$\log V_R$	3.762	3.115	3.105	2.988	2.852	2.786	2.750
$20 \log V_R$	75.24	62.30	62.10	59.76	57.04	55.72	55.00
TRANSMISSION LOSS							
dB Re 1 mv at 1"	0	12.94	13.14	15.48	18.20	19.52	20.24

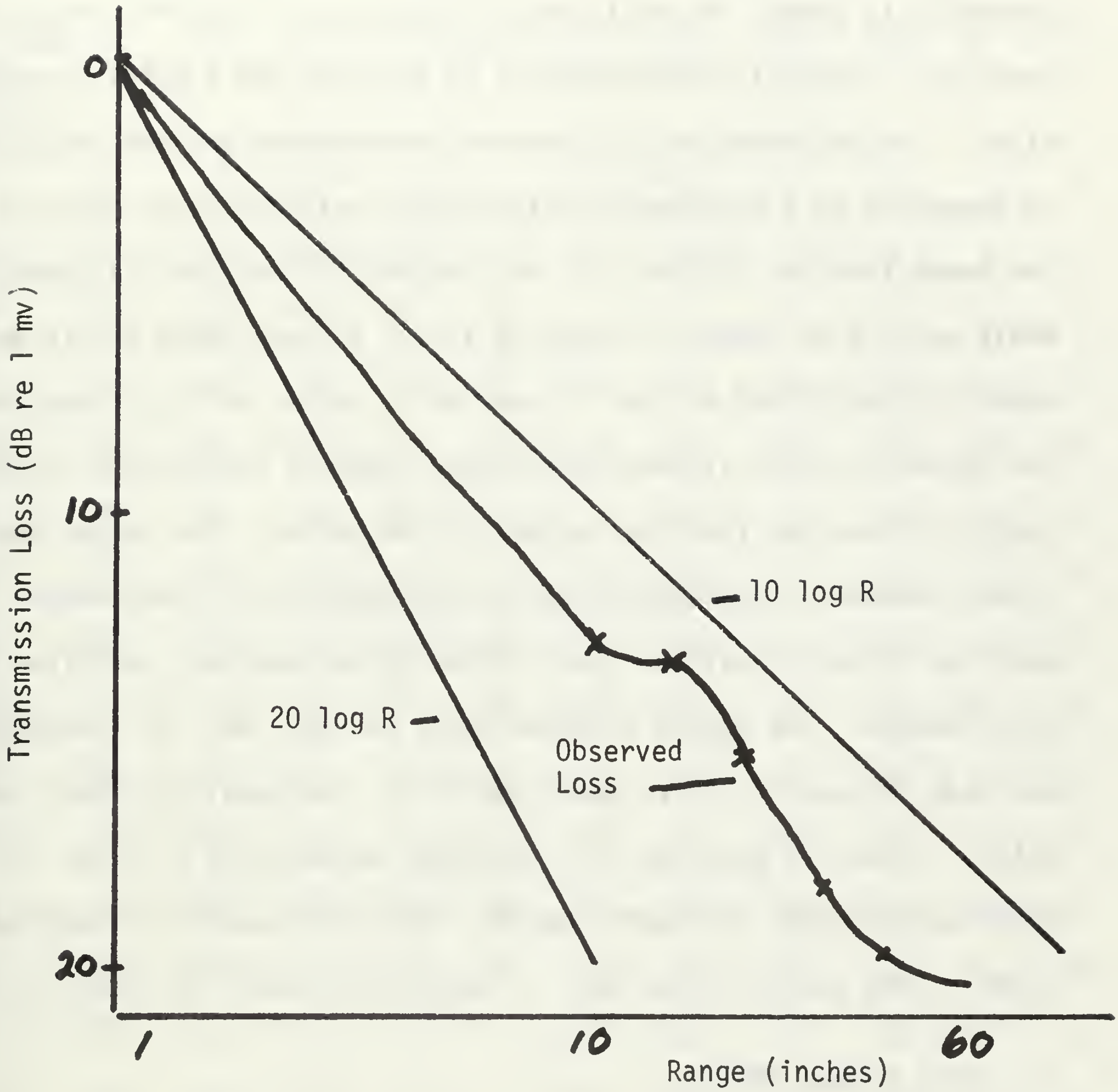


Figure 5 Transmission Loss Curve

Transmitter at mid-depth. Receiver levels averaged over depth for each range.

V. FINAL RESULTS

A. PROCEDURE

After preliminary results showed that the sonar and tank conformed generally to theory the next logical step was to find the target echo level in a vertical on-axis section of the tank for a particular situation. The existence of Lloyd mirror interference and the uncertainties in measuring to a wavelength dictated that only the gross features of the sound field be plotted. It was decided to take vertical measurements every five inches in range on axis. At each range the target was carefully positioned so that it was in the center of the primary beam. Two inches of water allowed forty-eight complete revolutions of the target drive screw from the surface to the bottom. The target was driven downward in two-revolution or one-twelfth inch increments. After each two turns the voltage level of the target echo was read from the oscilloscope. The system response level was 85.7 dB. An investigation was made for each of three sonar positions: surface, mid-depth, and bottom. Wood [2] mentions that overnight evaporation of water can drastically change the sound channel. For this reason all readings were taken in the course of one day. A sample data sheet is shown in Table II.

B. LLOYD MIRROR EFFECTS

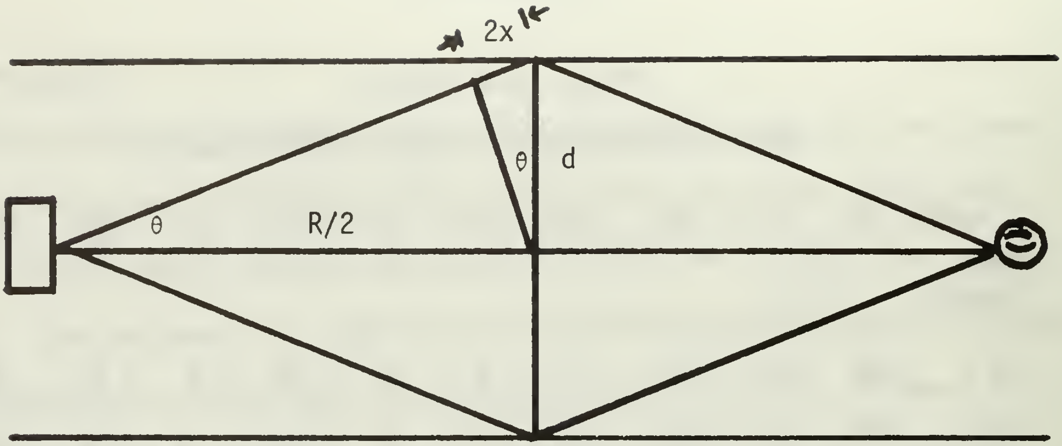
In order to find interference effects at the receiver from a distant target it is easiest to look at mid-depth along the range of the tank as shown in figure 6. The direct ray returns to the receiver with no phase change because the target is a rigid sphere. The air-water interface and the pressure release bottom each cause a 180 degree phase change per bounce and as a crude approximation the intensity of these rays are about

TABLE II

TARGET ECHO LEVELS

Sonar at mid-depth — levels in millivolts

RANGE / DEPTH (TURNS)	10"	15"	20"	25"	30"	35"	40"	45"	50"	55"	60"
10	50	0	15	5	0	0	0	0	0	0	0
12	80	90	40	25	5	10	10	5	5	5	0
14	80	130	75	50	25	5	5	30	10	15	15
16	60	100	75	60	30	10	20	30	10	20	30
18	80	80	40	50	30	30	25	30	20	30	20
20	80	70	40	50	50	70	30	15	30	20	10
22	90	70	35	60	60	75	50	10	30	10	10
24	120	70	40	60	60	70	25	10	20	15	15
26	160	70	50	60	60	40	30	15	5	10	20
28	140	60	60	60	60	30	40	30	15	40	30
30	20	50	75	70	60	40	35	35	10	60	50
32	50	100	110	60	50	60	40	30	20	40	70
34	130	100	130	70	70	70	20	30	10	50	60
36	160	100	120	60	75	80	50	20	40	50	40
38	150	120	100	70	70	100	50	5	60	30	30
40	110	140	140	40	100	100	40	50	50	50	35
42	160	120	100	10	150	80	60	70	30	60	40
44	200	120	100	50	180	60	50	50	10	60	35
46	240	90	90	40	200	70	10	30	30	60	30
48	250	100	90	40	30	70	40	20	40	50	20



$$\text{SIN} \quad = \frac{d}{R/2} = \frac{2x}{d}$$

$$x \quad = \frac{d^2}{R}$$

Total extra distance traveled by one surface or bottom reflected ray to target and back equals 4x.

Figure 6 Extra Distance Traveled By A Reflected Ray half of the direct ray due to the half-power points of the major beam lobe. It then follows that the combination of these rays will return lagging the direct ray due to the extra distance travelled with an equal intensity. The equation given for Lloyd mirror effects in Section II-D then reduces to:

$$I = I_o(2 + 2 \cos \omega\tau)$$

Figure 6 shows the extra distance travelled is 4x. Therefore:

$$\tau = \frac{4x}{f\lambda}$$

and

$$\omega\tau = \frac{2\pi f\ 4x}{f\lambda} = \frac{8\pi d^2}{\lambda r}$$

Therefore

$$I = I_o(2 + 2 \cos \frac{8\pi d^2}{\lambda r})$$

Then we should have a maximum return echo when $\frac{8d^2}{\lambda r}$ is an even integer and we should have cancellation where $\frac{8d^2}{\lambda r}$ equals an odd integer. Letting $d = 1"$ and $\lambda = .059"$ the following maximum and minimum positions are found.

Range (inches)

Max.	13.5		17		22.5		34		67
Min.		15		19		27		45	

The data from Table II for 32 turns indicates those positions where the target is at mid-depth. These voltage levels are converted to decibels and plotted on figure 7 from 25 to 60 inches. Also plotted are the theoretical values found above reduced appropriately from system response level for cylindrical spreading and target strength.

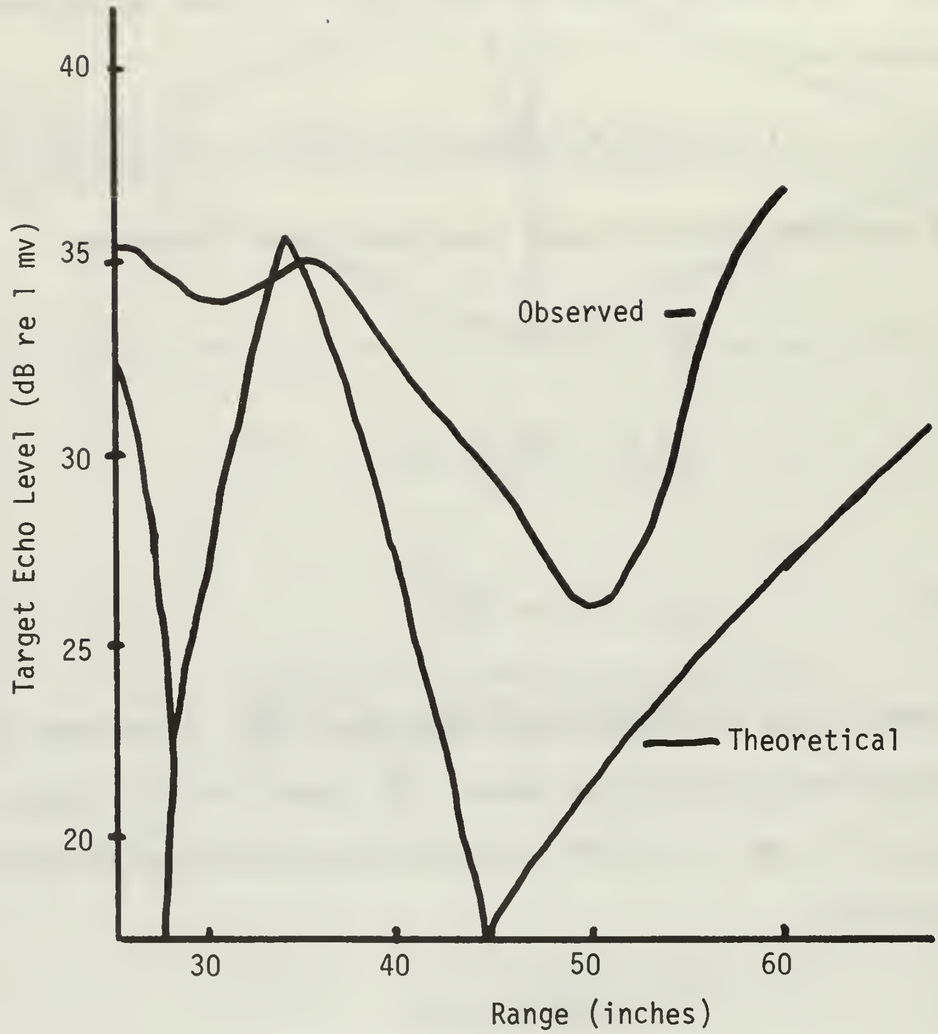


Figure 7 Lloyd Mirror Effects

C. VERTICAL CROSS SECTION

The values in Table II indicate many peaks and nulls in any vertical cross section. This is predicted by Normal Mode theory and by Lloyd mirror effects and was also found by Wood [3]. Because the target was positioned at five inch down-range intervals there is little correlation between any two successive down-range measurements except in the far field. Figure 8 shows two typical vertical cross sections for the sonar at mid-depth and the target at 55 and 60 inches down-range. Note that the echo levels indicate a generally higher intensity near the bottom due to increasing target strength of the target stem.

D. DOWN-RANGE MEASUREMENTS

There are many ways to present the down range target echo levels. In an actual case in the ocean the target depth is generally unknown, therefore averaging the values over all depths at each range and sonar position might be the most meaningful. In addition averaging over depth would eliminate changes in target strength caused by the target mounting rod. Table III goves a sample calculation for the mid-depth sonar position. Figure 9 shows the target echo levels plotted against range. The system source level is the same 85.7 dB obtained in Section IV-B.

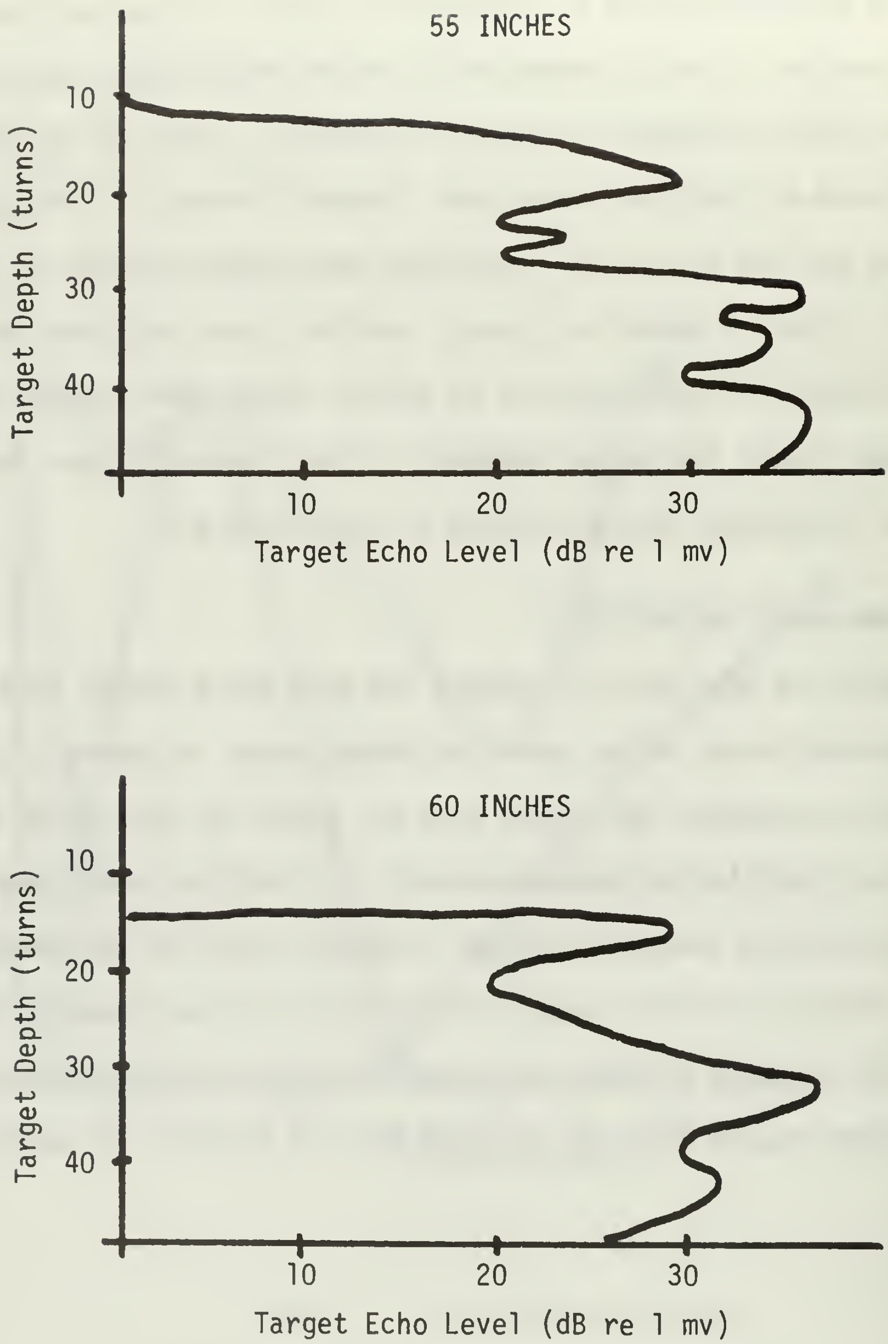


Figure 8 Typical Vertical Cross-sections for Sonar at Mid-Depth

TABLE III

TARGET ECHO LEVEL: SONAR AT MID-DEPTH

RANGE (inches)	TOTAL VOLTAGE (millivolts)	AVERAGE VOLTAGE (millivolts)	INTENSITY LEVEL (dB re 1 mv)
10	2410	120.5	41.6
15	1780	89.0	39.0
20	1525	76.3	37.6
25	990	49.5	33.8
30	865	43.3	32.6
35	870	43.5	32.8
40	630	31.5	30.0
45	515	25.7	28.2
50	445	22.3	27.0
55	675	33.7	30.6
60	560	28.0	29.0

Total voltage is the sum of all voltages at each depth.

Average voltage is total voltage divided by twenty.

Intensity level is twenty times the logarithm of average voltage.

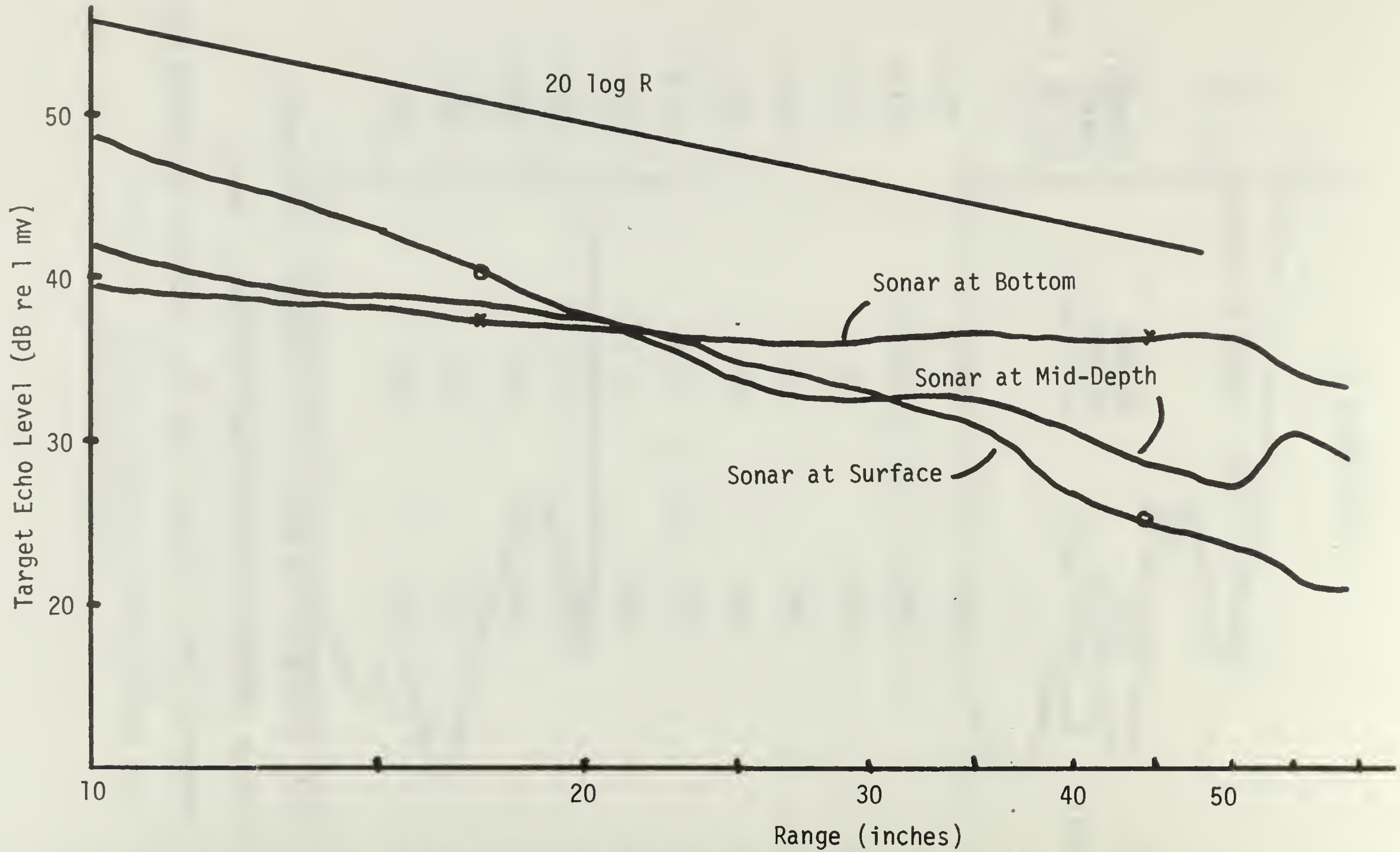


Figure 9 Down-Range Echo Levels Averaged Over Depth at Each Range

VI. DISCUSSION OF DATA

As could be expected in a shallow water environment the data do not follow theory exactly. Many factors were uncontrolled in this experiment but some observations could be made on the most obvious of the variances with theory.

The Lloyd mirror comparison in figure 6 indicates only a bare degree of compatibility between theory and data. However, although the correlation is not great it is felt that the ray assumptions used in the derivation of the theoretical values were the major contributing difference. Lloyd mirror effects have been confirmed by many researchers for omni-directional source in a laboratory tank. It is only natural to assume they would be present for a directional source. In addition, projecting the "beam concept" down-range, it would seem that rays separated by only a few hundredths of a degree could exhibit Lloyd mirror effects at a great range. This subject of beam studies in a shallow channel is beyond the scope of this paper.

Table II and figure 8 indicate a higher target echo level as the target was screwed towards the bottom. This "bunching" of target level with depth is probably due to the target strength of the mounting stem of the sphere. The exact amount of increase in target strength due to increasing target depth could be obtained in future experiments by driving down the stem only and then reducing the value for stem and sphere appropriately.

The down-range echo levels for the surface and mid-depth sonar generally follow a cylindrical spreading law reduced by an initial amount to allow for spherical spreading. (Note that in a two way situation

20 log R denotes cylindrical spreading and 40 log R denotes spherical spreading). However, with the sonar positioned at the bottom, the losses do not follow a cylindrical spreading law. It is easy to observe that at ten inches the bottom sonar echo levels are least, possibly indicating a bottom loss on the first bounce. One might also say that at about twenty-two inches the three sonar position echo levels have suffered equal losses. But at 60 inches the bottom sonar has suffered the least loss which would negate any constant dB loss per bounce conclusion. It is recommended therefore that in future experiments more care be taken in selecting and evaluating the qualities of a laboratory tank bottom and lining.

VII. CONCLUSIONS

The objectives of this paper were threefold: to construct a scale model sonar, to determine a set of equations suitable for model studies, and to compare results with theory. The piston transducers used in this experiment were adequate and provided characteristics similar to any modern sonar. However in future work only one transducer with an adequate TRANSMIT-RECEIVE switch would be closer to reality. A simple signal processing system that involved square-law signal detection with and without a time integration scheme would also provide more rapid and accurate readings and would allow for energy as well as power studies.

The tank dimensions and frequency used were not really compatible for long range scaling studies. These parameters constitute a trade-off in any model study. Either the size of the tank must be increased or the frequency must be increased. The penalty for a larger tank is more space is required and control of acoustic parameters becomes more difficult. The penalty for higher frequencies is that extremely precise measuring equipment is necessary.

The equations developed were entirely satisfactory. The system response level concept was useful and seems reasonable for use with piston transducers with low output. The decibel reference to one millivolt is compatible with standard laboratory equipment. The elimination of the noise term from the Sonar Equation was allowable in this experiment because studying a noise-limited or reverberation-limited case would have been of little value at the ranges modeled.

The comparisons between theory and data of this model were as good as those of the other shallow water models currently in use, especially when a particular empirical model is used with another author's data. The discrepancies noted in the previous section and those documented throughout the available literature only point to the necessity for more, closely controlled, laboratory model experiments.

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13. ABSTRACT

An experiment was performed in a small laboratory tank to study the feasibility of modeling an active sonar in a shallow water environment. The modeling frequency of 1000 kHz in a two meter tank indicated fair compatibility with theory for the short scaled ranges studied. An initial spherical spreading loss followed by a cylindrical spreading loss, bottom loss effects, and Lloyd mirror interference were observed. The methods were suitable for future modeling experiments.

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